HIRDLS

SW	OXF	190	B

HIGH RESOLUTION DYNAMICS LIMB SOUNDER

Originator: C. W. P. Palmer **Date: 981111**

Subject/title: Radiometric Calibration Algorithms

Contents

Changes for this version: Introduction of the concept of a Virtual Blackbody View to clarify discussion of the radiometric calibration algorithm.

Key words: radiometric, calibration, in-flight calibration, software, algorithm

---

Reviewed/approved by:			
Date (yymmdd):			

OXFORD UNIVERSITY
Atmospheric, Oceanic and Planetary Physics
Parks Road
OXFORD OX1 3PU
United Kingdom

EOS

This page intentionally left blank

1 Introduction

This purpose of this document is to define operational calibration algorithms for Level 1 radiometric calibration. Applicable reference documents include

- SC-HIR-18K Instrument Requirements Document (IRD)
- TC-OXF-97A RADMETAC Budget Description.

Section 2 describes the radiometric model which underlies the proposed algorithms, in a form which may be used in the algorithm theoretical basis document. Section 3 gives the suggested outlines of operational algorithms. Section 4 summarizes the software requirements.

2 Radiometric Model

The radiometric model described in this section is based on that developed in TC-OXF-97A, slightly extended, and with explicit allowance for non-linearity.

We shall define four classes of instrument view:

1. Atmospheric Views: Views through the hot-dog aperture with tangent height below the minimum space view height given in the IRD.
2. Space Views: Views through the hot-dog aperture with tangent height above the minimum space view height given in the IRD.
3. Blackbody Views: Views properly aligned on the IFC Blackbody *via* the Calibration Mirror M6.
4. Invalid Views: All other views, in which the radiometer beam does not pass cleanly through the aperture, or is obstructed by the door, or is not properly aligned with the IFC Blackbody.

Note that the division between 1 and 2 is channel-dependent: the minimum space view heights vary from channel to channel, so that (for example) there is a considerable range of the elevation scan for which channel 5 (minimum space view height 150 km) will be obtaining Atmospheric Views while channels 17 and 18, (same row but minimum space view height 75 km) will be obtaining Space Views. In principle the distinction between Invalid Views and the other three classes could also be channel dependent, but we shall assume initially that if any channel has an Invalid View then all channels do. We shall assume that Invalid Views are in general worthless and not discuss them further. (There may be particular tests, for example the scanning test over the IFC aperture, when Invalid Views are used, but these will have special analysis software. However there may be a need for a special Test View class, identified by a telemetry flag.)

We next define a mathematical model relating the output count from a given channel, for each class of view, to the various sources of chopped radiance, including the atmospheric radiance we wish to measure. This will follow the treatment in TC-OXF-97A with some modifications, which we list here for ease of comparison.

1. There is more information regarding the offset count than is allowed for in TC-OXF-97A, because the offset referred to in TC-OXF-97A as the electronic offset is largely a digital offset, added in software, and this part of it is therefore a known number (C_1 in (8) below).

2. The treatment in TC-OXF-97A is explicitly linear, with non-linearity only appearing in the error budget (where it is described as uncorrected non-linearity, with no hint as to how it might be corrected!) whereas here a slightly non-linear algorithm is proposed.
3. Certain effects which are discussed in TC-OXF-97A will not be covered here because they cannot be incorporated into the model, and can only be handled by the error budget. These are diffraction of earthshine and scattering within the optics (the y, z, y' and z' terms of TC-OXF-97A).

We shall use the following conventions for symbols throughout:

L is a spectral radiance averaged spatially and spectrally over the radiometer beam for a given channel.

$B(T)$ is a Planck spectral radiance at temperature T averaged spectrally for a given channel.

R is a mirror reflectance; the corresponding emissivity ε is given by $1 - R$.

S is a channel telemetry count.

ϵ denotes the line-of-sight elevation angle, and is used as an argument to quantities that vary with angle.

ϕ denotes the line-of-sight azimuth angle, and is used as an argument to quantities that vary with angle.

t denotes time, and is used as an argument to quantities that may vary significantly with time over a calibration period (a minute, a day) — mainly temperatures. Other quantities (such as emissivities) may vary over longer periods, but this dependence is not indicated.

Subscripts are used to distinguish quantities of the same type, using the standard abbreviations for the optical components:

FM0 Scan Mirror

M1 Telescope primary mirror

FM3 Mirror chopper

M5 Chopper space view mirror

M6 Calibration mirror

BB Blackbody

FS1 Field stop 1, immediately after the chopper

SPV Space View.

We first discuss the Space and Atmospheric Views, which are described by the same model, with zero atmospheric radiance in the Space View. The sources of chopped radiance in these views are as follows, evaluated at FS1:

- Atmospheric Radiance reflected by the scan mirror FM0 and the telescope primary M1; the reflectance of the scan mirror is angle-dependent: $R_{\mathrm{M1}} R_{\mathrm{FM0}}(\epsilon, \phi) L$.

- Radiance emitted by the scan mirror FM0 and reflected by the primary M1; the effective temperature of the scan mirror is angle-dependent through the change in beam footprint: $R_{\rm M1}\varepsilon_{\rm FM0}(\epsilon,\phi)B(T_{\rm FM0}(t,\epsilon,\phi))$.
- Radiance emitted by the primary M1: $\varepsilon_{\rm M1}B(T_{\rm M1}(t))$.
- Radiance incident at the space view port and reflected by the chopper space view mirror M5 and the chopper FM3: $R_{\rm FM3}R_{\rm M5}L_{\rm SPV}$. (In orbit $L_{\rm SPV}=0$; in pre-launch calibration this may not be true, but the time-variation of $L_{\rm SPV}$ is negligible.)
- Radiance emitted by the chopper space view mirror M5 and reflected by the chopper FM3: $R_{\rm FM3}\varepsilon_{\rm M5}B(T_{\rm M5}(t))$.
- Radiance emitted by the chopper FM3: $\varepsilon_{\rm FM3}B(T_{\rm FM3}(t))$.

The amplitude of the chopped radiance signal following the chopper is thus given by the difference between the radiances transmitted and reflected by the chopper:

$$\begin{aligned}\Delta L_{\rm FS1}(L,\epsilon,\phi,t) \;=\;& R_{\rm M1}R_{\rm FM0}(\epsilon,\phi)L \;+\; R_{\rm M1}\varepsilon_{\rm FM0}(\epsilon,\phi)B(T_{\rm FM0}(t,\epsilon,\phi)) \;+\; \varepsilon_{\rm M1}B(T_{\rm M1}(t))\\ &-\,R_{\rm FM3}R_{\rm M5}L_{\rm SPV} \;-\; R_{\rm FM3}\varepsilon_{\rm M5}B(T_{\rm M5}(t)) \;-\; \varepsilon_{\rm FM3}B(T_{\rm FM3}(t)).\end{aligned} \tag{1}$$

This chopped radiance signal is the input to the remainder of the radiometer, and generates an output telemetry count S given by a slightly nonlinear function of $\Delta L_{\rm FS1}$:

$$S = C_1 + g_{\rm FS1}(\Delta L_{\rm FS1}) \tag{2}$$

where C_1 is the known offset count added in software to ensure that S is always positive, and all other effects are included in the response function $g_{\rm FS1}$. Because the non-linearity is expected to be small ($\lesssim 1\%$) a suitable approximation to $g_{\rm FS1}$ is

$$g_{\rm FS1}(\Delta L_{\rm FS1}) = C_2(t) + G_{\rm FS1}(t)\Delta L_{\rm FS1}\Big(1 - k_{\rm FS1}\,\Delta L_{\rm FS1}\Big) \tag{3}$$

where C_2 is an additional offset due to small pick-up effects ('cavity flicker', crosstalk) which are present when $\Delta L_{\rm FS1}=0$, $G_{\rm FS1}$ is the FS1-to-telemetry gain and $k_{\rm FS1}$ takes account of the small non-linearity. Note that, with this representation of the non-linearity, $G_{\rm FS1}$ is the 'small signal' gain: the slope of $g_{\rm FS1}$ at $\Delta L_{\rm FS1}=0$.

In (3) the FS1-to-telemetry gain $G_{\rm FS1}$ is given by

$$G_{\rm FS1}(t) = A\Omega\Delta\nu\,\tau\,2PK\sum_n F(n\nu_{\rm ch})\mathcal{C}_n\cos\delta\psi_n \tag{4}$$

where

$A\Omega\Delta\nu$ are the radiometer beam parameters;

τ is the optical transmission from after the chopper to the detector;

P is the (small signal) responsivity of the detector and bias network (Volts/Watt) (DSS part of the signal chain);

$F(n\nu_{\rm ch})$ is the gain of the anti-aliasing filter at frequency $n\nu_{\rm ch}$;

$\mathcal{C}_n$ is the amplitude of the n'th harmonic in the Fourier expansion of the chopper waveform for unit ΔL. (For example, $\mathcal{C}_1 = 2/\pi$ for a perfect square wave);

$\cos\delta\psi_n$ is the phase difference between the sampling time and the maximum of the n'th harmonic;

K is the digitization constant (counts/Volt);

and finally the factor of two comes from the sampling of the wave at both maximum and minimum, giving a difference of twice the amplitude.

Obviously several of these factors may be time-dependent, so that G_{FS1} is shown as time-dependent. (According to TC-LOC-236A the only factors with significant time-dependence are P and $\mathcal{C}_n \cos\delta\psi_n$.) G_{FS1} is approximately the quantity to which the gain stability requirement in the RADMETAC budget applies — strictly speaking this includes R_{M1} as well. The end-to-end gain G used in TC-OXF-97A is given by

$$G = R_{\mathrm{FM0}}(\epsilon,\phi) R_{\mathrm{M1}} G_{\mathrm{FS1}}. \tag{5}$$

The chopped radiance at FS1, ΔL_{FS1}, while an obvious factor to introduce into the radiometric model, is not something we are interested in as such, nor do we have direct control over it in calibration. We therefore wish to define an equivalent chopped radiance at the entrance pupil:

$$\Delta L = \frac{\Delta L_{\mathrm{FS1}}}{R_{\mathrm{FM0}}(\epsilon,\phi) R_{\mathrm{M1}}} = L + L_3 \tag{6}$$

where L_3 is a radiometric offset given by the instrumental chopped radiance sources in (1) divided by $R_{\mathrm{M1}} R_{\mathrm{FM0}}(\epsilon,\phi)$:

$$\begin{aligned} L_3 \quad = \quad & \frac{\varepsilon_{\mathrm{M1}} B(T_{\mathrm{M1}}(t)) - R_{\mathrm{FM3}} R_{\mathrm{M5}} L_{\mathrm{SPV}} - R_{\mathrm{FM3}} \varepsilon_{\mathrm{M5}} B(T_{\mathrm{M5}}(t)) - \varepsilon_{\mathrm{FM3}} B(T_{\mathrm{FM3}}(t))}{R_{\mathrm{M1}} R_{\mathrm{FM0}}(\epsilon,\phi)} \\ & + \frac{\varepsilon_{\mathrm{FM0}}(\epsilon,\phi) B(T_{\mathrm{FM0}}(t,\epsilon,\phi))}{R_{\mathrm{FM0}}(\epsilon,\phi)}. \end{aligned} \tag{7}$$

Note that the effect of referring the gain to the entrance pupil in (5) is that it acquires angle-dependence through R_{FM0}, and similarly the offset in (7) acquires further angle-dependence, in addition to $\varepsilon_{\mathrm{FM0}} B(T_{\mathrm{FM0}})$. In terms of these quantities we can re-write (2) as

$$S = C_1 + g(\Delta L). \tag{8}$$

To the same approximation as (3) we can write $g(\Delta L)$ as

$$g(\Delta L) = C_2(t) + G\,\Delta L\Big(1 - k\,\Delta L\Big) \tag{9}$$

where G is given by (5) and $k = R_{\mathrm{M1}} R_{\mathrm{FM0}} k_{\mathrm{FS1}}$. Equations (8) and (9) are the non-linear form of equation (3) of TC-OXF-97A, where G is equivalent to G defined there, and the offset C in TC-OXF-97A has been split into three parts, a known digital offset C_1, a small pickup offset C_2 and a radiometric offset GL_3.

We require, in addition, the inverse function giving L as a function of S. We define $\Delta S = S - C_1$, the actual counts difference from the digital sampling without the constant added in software. We define $\tilde{g}$ to be the inverse function to g:

$$\Delta L = \tilde{g}(\Delta S). \tag{10}$$

An approximate form for $\tilde{g}$ can be written in the same form as the approximation (9) for g:

$$\tilde{g}(\Delta S) = L_2 + \frac{\Delta S}{G}\Big(1 + \tilde{k}\,\Delta S\Big) \tag{11}$$

The two approximations are not exactly equivalent, in the sense that they are not inverses of each other, but the coefficients are approximately related by $L_2 = -C_2/G$ and $\tilde{k} = k/G$. The small pick-up offset now appears as the chopped radiance required to give zero chopped signal count, instead of the chopped signal count resulting from zero chopped radiance. Whether k or $\tilde{k}$ is a constant, or whether $\tilde{k}$ is a function of G, will be determined in pre-launch calibration. My best guess is that $\tilde{k}$ will be more constant than k as the gain changes with detector temperature, as there are theoretical arguments that suggest that the non-linearity will diminish as the gain diminishes.

We now adapt this radiometric model to deal with Blackbody views. In Blackbody Views we have a known (approximately) radiance at the entrance pupil, made up of

- Radiance from within the Optical Bench enclosure reflected from the IFC Blackbody, and reflected from the IFC calibration mirror M6: $(1 - \varepsilon_{\mathrm{BB}}) R_{\mathrm{M6}} L_{\mathrm{OB}}$;
- Radiance emitted by the IFC Blackbody, and reflected from the IFC calibration mirror M6: $\varepsilon_{\mathrm{BB}} R_{\mathrm{M6}} B(T_{\mathrm{BB}}(t))$;
- Radiance emitted by the IFC calibration mirror M6: $\varepsilon_{\mathrm{M6}} B(T_{\mathrm{M6}}(t))$.

We can combine these to give

$$L_{\mathrm{BB}} = B(T_{\mathrm{BB}}) + (1 - \varepsilon_{\mathrm{BB}}) R_{\mathrm{M6}} \Big(L_{\mathrm{OB}} - B(T_{\mathrm{BB}}) \Big) + \varepsilon_{\mathrm{M6}} \Big(B(T_{\mathrm{M6}}) - B(T_{\mathrm{BB}}) \Big). \tag{12}$$

However we have no knowledge of L_{OB}, so we drop this term from the model as the whole of it is included in the RADMETAC budget, effectively setting $\varepsilon_{\mathrm{BB}} = 1$:

$$L_{\mathrm{BB}} = B(T_{\mathrm{BB}}(t)) + \varepsilon_{\mathrm{M6}} \Big(B(T_{\mathrm{M6}}(t)) - B(T_{\mathrm{BB}}(t)) \Big). \tag{13}$$

(L_{BB} was called $B(T_c)$ in TC-OXF-97A; since it is not strictly a Planck function the notation has been altered.) This radiance enters the radiometric model defined by equations (6), (7), (8) and (10) in place of the atmospheric radiance L.

This completes the radiometric model relating telemetry counts to radiances. The model uses about 17 parameters in addition to the unknown atmospheric radiance L: L_{SPV}, six Planck functions, five reflectances, the two offsets C_1 and C_2, G_{FS1} and k, many of which are time- or angle-dependent. Although we have some knowledge of most of these parameters at launch, and in some cases throughout the mission, we need to devise a calibration algorithm that is robust in the presence of errors in this knowledge. Some of the complexity is removed if we use the radiometric offset L_3 as a parameter; this reduces the number of parameters entering the model to ten: G, k or $\tilde{k}$, C_1, C_2 or L_2, L_3, three Planck functions and two reflectances. However, both G and L_3 have significant time-dependence and angle-dependence.

3 Calibration Algorithms

There are three requirements for the inversion of the radiometric model defined above to give a radiance from an observed telemetry count: knowledge of the radiometric offset in the atmospheric view, knowledge of the blackbody signal level in the atmospheric view, and knowledge of the inverse function $\tilde{g}$. We start by supposing these three problems solved. Firstly we define the Virtual Space View $S_{v0}(t, \epsilon, \phi)$ as the count we would have observed at the time and mirror angle of the atmospheric view if there had been zero input radiance. Secondly we define a Virtual

Blackbody View $S_{v\mathrm{BB}}(t, \epsilon, \phi)$ as the count we would have observed at the time and mirror angle of the atmospheric view if the input radiance had been the blackbody radiance L_{BB} given by (13). Thirdly we suppose $\tilde{g}$ known. These counts are related to radiances by (10):

$$\begin{array}{rrcl}
\text{Atmospheric View:} & L + L_3 & = & \tilde{g}(S - C_1) \quad (14)\\
\text{Virtual Space View:} & L_3 & = & \tilde{g}(S_{v0}(t, \epsilon, \phi) - C_1) \quad (15)\\
\text{Virtual Blackbody View :} & L_{\mathrm{BB}} + L_3 & = & \tilde{g}(S_{v\mathrm{BB}}(t, \epsilon, \phi) - C_1) \quad (16)
\end{array}$$

From these equations we can easily derive the atmospheric radiance:

$$L = L_{\mathrm{BB}} \frac{\tilde{g}(S - C_1) - \tilde{g}(S_{v0}(t, \epsilon, \phi) - C_1)}{\tilde{g}(S_{v\mathrm{BB}}(t, \epsilon, \phi) - C_1) - \tilde{g}(S_{v0}(t, \epsilon, \phi) - C_1)}. \quad (17)$$

We note that, because both numerator and denominator are given by differences of $\tilde{g}$ functions we do not need to know any *constant* offsets in $\tilde{g}$ and, similarly, because of the ratio of functions we do not need to know any overall scaling factor. In terms of our approximate form (11) for $\tilde{g}$, we do not need to know L_2 or G, but only $\tilde{k}$, which must be measured and characterised in pre-launch calibration. This is the knowledge required of $\tilde{g}$, leaving only the derivation of the virtual views $S_{v0}(t, \epsilon, \phi)$ and $S_{v\mathrm{BB}}(t, \epsilon, \phi)$.

The Virtual Space View $S_{v0}(t, \epsilon, \phi)$ has to be derived from the actual Space Views. Although this is shown as having quite complex dependences, the variation is expected to be quite small over one elevation scan, a few times the IRD NEN level according to TC-OXF-97A. The simplest approach is to extrapolate whatever linear dependence is observed in space views on the same elevation scan. These are all at the same (mirror) azimuth, and are taken with ϵ a linear function of t, apart possibly from an initial acceleration period, so a single linear dependence on either ϵ or t is the most that can be derived from this data. Over the limited time span of a single scan it is quite likely that the actual space views are consistent with a constant, and there is no useful trend information beyond an upper limit. If this upper limit is too large to meet the systematic accuracy requirements then other sources of information may need to be used - data taken during 'flyback' from one end of the azimuth range to the other, data from other azimuths, data at the same azimuth from previous swaths, pitch-down data. The approach used will doubtless be refined when we have real data, but the initial approach should be simple, and based on the assumption that the changes from the top-of-scan are small.

The Virtual Blackbody View $S_{v\mathrm{BB}}(t, \epsilon, \phi)$ has to be derived from the actual Blackbody Views. These are all taken under the same conditions of mirror angle, and differ only in the blackbody temperatures, mirror temperatures and gain for different views. These variations, over the period between Blackbody Views, are expected to lead to changes in the Blackbody Views that are small compared with the overall systematic accuracy of gain measurement (0.5% or 1% depending on channel), but quite possibly large compared with the noise, because of the very large signal:noise ratio in Blackbody Views. By interpolation in time we can thus derive a slightly different virtual Blackbody View with great accuracy: the count we would have observed if we had tilted the mirror to look at the blackbody in the usual way at the time of the atmospheric observation. The calibration radiance corresponding to this view is $L_{\mathrm{BB}}(t)$ given by (13) with the IFC temperature and IFC calibration mirror temperature evaluated at the time of the atmospheric view. We shall refer to this Interpolated Blackbody View as $S_{i\mathrm{BB}}(t)$.

We now compare the Interpolated Blackbody View with the Virtual Blackbody View, using the radiometric model derived in section 2. Because both views are at the same time, they differ only because of the angle-dependence. If we use the formulation in terms of g_{FS1}, all the angle-dependence is then in the chopped radiance ΔL_{FS1}. The Interpolated Blackbody View is related to radiance by (2):

$$S_{i\mathrm{BB}}(t) = C_1 + g_{\mathrm{FS1}}(\Delta L_{\mathrm{FS1}}(L_{\mathrm{BB}}, \epsilon_{\mathrm{BB}}, \phi_{\mathrm{BB}}, t)) \tag{18}$$

where the chopped radiance is given by (1). The Virtual Blackbody View we require, using the same calibration radiance, is

$$S_{v\mathrm{BB}}(t) = C_1 + g_{\mathrm{FS1}}(\Delta L_{\mathrm{FS1}}(L_{\mathrm{BB}}, \epsilon, \phi, t)). \tag{19}$$

Equations (18) and (19) only differ in the angle-dependence of the chopped radiance, and this dependence is extremely small. This fact was emphasized in TC-OXF-97A, and follows from the fact that the scan mirror is at a very similar temperature to the IFC BB, and that its reflectance varies very little with angle. If we simply evaluate the difference between the two chopped radiances, all the instrumental offsets vanish except those from the scan mirror:

$$\begin{aligned} R_{\mathrm{M1}}\Big(&R_{\mathrm{FM0}}(\epsilon_{\mathrm{BB}}, \phi_{\mathrm{BB}})L_{\mathrm{BB}} + \varepsilon_{\mathrm{FM0}}(\epsilon_{\mathrm{BB}}, \phi_{\mathrm{BB}})B(T_{\mathrm{FM0}}(t, \epsilon_{\mathrm{BB}}, \phi_{\mathrm{BB}})) \\ &-R_{\mathrm{FM0}}(\epsilon, \phi)L_{\mathrm{BB}} - \varepsilon_{\mathrm{FM0}}(\epsilon, \phi)B(T_{\mathrm{FM0}}(t, \epsilon, \phi))\Big) \end{aligned} \tag{20}$$

There are various ways of splitting this up, but one way of re-writing (20), using $R + \varepsilon = 1$ is

$$\begin{aligned} & R_{\mathrm{M1}}\Big(R_{\mathrm{FM0}}(\epsilon_{\mathrm{BB}}, \phi_{\mathrm{BB}}) - R_{\mathrm{FM0}}(\epsilon, \phi)\Big)\Big(L_{\mathrm{BB}} - B(T_{\mathrm{FM0}}(t, \epsilon_{\mathrm{BB}}, \phi_{\mathrm{BB}}))\Big) \\ + \quad & R_{\mathrm{M1}}\varepsilon_{\mathrm{FM0}}(\epsilon, \phi)\Big(B(T_{\mathrm{FM0}}(t, \epsilon_{\mathrm{BB}}, \phi_{\mathrm{BB}})) - B(T_{\mathrm{FM0}}(t, \epsilon, \phi))\Big). \end{aligned} \tag{21}$$

The first term represents the effect of the change in scan mirror reflectivity between Blackbody and Atmospheric view, estimated at about 0.06%, multiplied by the difference in Planck functions, which depends on the temperature difference, but is probably not more than 25% of L_{BB} in the worst case channel. The first term is therefore estimated to be about a few times $10^{-4}L_{\mathrm{BB}}$. The second term is due to the change in footprint on the scan mirror, coupled with a temperature distribution across it. Even assuming a very large temperature structure of about 1 K, the change in the mean is estimated at no more than about 100 mK, which gives an error on the order of $10^{-4}L_{\mathrm{BB}}$.

These terms are covered by the RADMETAC budget — they are effectively the x' and Scan Mirror T Non-Uniformity terms. To within this very small error we can identify the Interpolated Blackbody View as the Virtual Blackbody View we require:

$$S_{v\mathrm{BB}}(t) = S_{i\mathrm{BB}}(t, \epsilon, \phi). \tag{22}$$

Note that this implies that $S_{v\mathrm{BB}}$ is, in fact, *not* significantly angle-dependent. In terms of the radiometric model we have developed, the change in reflected calibration radiance at the scan mirror is compensated for by the change in emitted radiance by the scan mirror, in exactly the same way as at the calibration mirror M6. Note further that although we have no reason to doubt this compensation we cannot verify it. All we can do is measure the angle-dependence of the Space View, and this tells us nothing about the compensation between this and the angle-dependent gain.

We have now defined all the factors in the calibration algorithm (17). Inserting the approximate form for $\tilde{g}$ from (11) we obtain

$$L = L_{\mathrm{BB}}\,\frac{S - S_{v0}}{S_{v\mathrm{BB}} - S_{v0}}\,\frac{1 + \tilde{k}(S + S_{v0} - 2C_1)}{1 + \tilde{k}(S_{v\mathrm{BB}} + S_{v0} - 2C_1)}. \tag{23}$$

If define the normalized calibrated radiance $\mathcal{L} = L/B(T_0)$, where T_0 is a standard temperature, and substitute L_{BB} from (13) we obtain our final algorithm:

$$\mathcal{L} = \frac{S - S_{v0}}{S_{v\mathrm{BB}} - S_{v0}} \frac{1 + \tilde{k}(S + S_{v0} - 2C_1)}{1 + \tilde{k}(S_{v\mathrm{BB}} + S_{v0} - 2C_1)} \frac{B(T_{\mathrm{BB}}(t)) + \varepsilon_{\mathrm{M6}}(B(T_{\mathrm{M6}}(t)) - B(T_{\mathrm{BB}}(t)))}{B(T_0)}. \tag{24}$$

An alternative approach to part of this problem would be to define linearized telemetry counts $\mathcal{S} = C_1 + (S - C_1)(1 + \tilde{k}(S - C_1))$. These could be calculated for all Level 0 radiance counts in a pre-processing stage, provided $\tilde{k}$ was adequately constant. In terms of these counts the first two factors in (24) can be written as the usual calibration ratio $(\mathcal{S} - \mathcal{S}_{v0})/(\mathcal{S}_{v\mathrm{BB}} - \mathcal{S}_{v0})$.

The $B(T)$ factors in the above equations are Planck functions averaged over the spectral bandpass of the relevant channel. If the spectral bandpass function is $F_{\mathrm{spec}}(\nu)$, normalized so that

$$\int F_{\mathrm{spec}}(\nu)\, d\nu = 1 \tag{25}$$

then $B(T)$ is given by

$$\int F_{\mathrm{spec}}(\nu)\, B(\nu, T)\, d\nu \tag{26}$$

where $B(\nu, T)$ is the Planck spectral radiance as a function of ν and T. Obviously we need to be able to evaluate this over a range of temperatures for each channel, using the measured spectral functions $F_{\mathrm{spec}}(\nu)$. One way of doing this would be with tables. I would propose the following alternative. We define the mean frequency for each channel:

$$\bar{\nu} = \int \nu F_{\mathrm{spec}}(\nu)\, d\nu. \tag{27}$$

In terms of this we evaluate $B(T)$ as

$$B(T) = B(\bar{\nu}, T) + \frac{1}{2}\frac{\partial^2 B}{\partial \nu^2}\delta\nu^2 \tag{28}$$

where

$$\delta\nu^2 = \int (\nu - \bar{\nu})^2 F_{\mathrm{spec}}(\nu)\, d\nu. \tag{29}$$

I have found this to be an excellent approximation at all temperatures except at temperatures so low that the answer is of no use. It is equivalent to approximating the Planck function over the width of the filter by a parabola. Channel 20 will be the worst case, and we could do numerical experiments using existing EM delivered data.

4 Software Requirements

1. Using scan mirror and door telemetry, a table or model of valid positions for views through the hot-dog aperture and blackbody views, orbit data and the list of minimum space view heights, assign every signal channel count to one of the four classes: Atmospheric, Space, Blackbody, Invalid. Consideration to be given to the best way of handling Test Views.

2. An interpolator in time, to generate the Virtual Blackbody View counts $S_{v\mathrm{BB}}$.

3. The blackbody temperature indicated as T_{BB} is in fact a weighted average over the three temperature sensors, using supplied weighting coefficients. Similar remarks apply to T_{M6}.

4. An interpolator in time and extrapolator in angle which can generate a virtual Space View S_0 at the time and angles corresponding to any Atmospheric View. There are several options here which need to be studied:
   (a) Use the Space Views on a given elevation scan to generate a straight line extrapolation. This may be too noisy.
   (b) Combine the Space Views on a given elevation scan with an *a priori* derived from pitch-down or other data.
   (c) Use all Space Views to update a radiometric model of S_0, in combination with pitch-down data, operated as a Kalman smoother. In principle the best approach, but probably ruled out by the absence of reliable emissivity data for most surfaces.
5. Tables or an algorithm to evaluate the filtered Planck function for each channel at any temperature. I would suggest the use of the algorithm above as an alternative to tables.
6. Using the interpolated/extrapolated values, apply the calibration algorithm (24) to every Atmospheric View.
7. Thought needs to be given to quality control in the interpolation/extrapolation process deriving all calibration data, since we will have a good idea of the expected value of any data item.